Wideband Planar Skirt Antenna and its Application for the Detection of Terahertz Radiation

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Abstract—A new type of traveling wave antenna is presented. Key features of the antenna are planar, low mass and wide bandwidth of operation. One such antenna was designed for terahertz radiation detection and realized in standard IBM CMOS-SOI process with subsequent MEMS post processing. Measurements performed at 655GHz showed very good agreement with the theoretical predictions based on full wave simulations. The present article describes the antenna physics, design, fabrication and measurement results.

Keywords— *Receiving antenna, Antenna theory, Microwave imaging, Microwave radiometry, Bolometers, Micromachining.*

I. INTRODUCTION

The field of terahertz (THz) radiation imaging has recently attracted considerable attention by numerous research groups all over the world, thanks to several perspective applications in the domains of astronomy and analytical science. Research effort concentrates on utilization of the THz spectrum for new applications such as THz security imaging that can reveal weapons hidden beneath clothing from distances of ten meters or more, medical THz imaging which can help locate skin cancer tumors beneath the skin and perform fully safe dental imaging. THz radiation is non-ionizing and is therefore safe to humans contrary to X-ray radiation that is being currently employed for imaging purposes. Promising results have also been obtained in the fields of non-destructive evaluation of materials and quality control [1].

Constructing THz detectors is typically a challenging endeavor due to lack of semiconductor based electronics compatible with such high frequencies of operation. A common method for constructing both transmitters and receivers is the photoconductive antenna which is made in most cases using III-V semiconductor like GaAs [2]. Another method for THz detection includes superconducting tunnel junctions [3] which require cooling the detectors down to 4 K.

THz imaging for security applications, for example, may use passive imaging technology, in order to avoid irradiating the person being interrogated. The capabilities of remote THz imaging without using any THz radiation source rely solely on the very low THz radiation power which is normally emitted by all bodies at room temperature, according to the well-

known black body radiation physics. Therefore, passive THz imaging requires extremely sensitive detectors capable of sensing this extremely low power radiation, which is three to four orders of magnitude smaller than in the far infra-red.

A THz detector is desirable that can be used to detect THz radiation and that has much lower potential cost compared to existing superconducting solutions and much higher sensitivity in comparison to existing photoconductive antennae. The envisioned sensor [4] is an antenna-coupled bolometer, i.e. an antenna designed to operate at THz frequencies and coupled to a resistive load (instead of a transmission line) which heats up due to the detected THz radiation, and its temperature is detected by an adjoining temperature sensor (MOSFET transistor in [4]).

This paper is outlined as follows: Section II briefly presents the antenna specifications for the THz detector. Section III elaborates on the physics behind the antenna behavior, and the reason for its wide bandwidth. Section IV provides a design of a skirt antenna and section V shows the final design and the measurement results. Finally, Section VI summarizes the results obtained so far.

II. ANTENNA SPECIFICATIONS

A. Antenna bandwidth

Due to lack of means of signal amplification at THz frequencies, the amount of energy received by an antenna is directly proportional to its operation bandwidth. The more radiation power is detected, the higher the resistive load temperature will rise, thus producing stronger electrical response. Therefore, in order to achieve the highest possible sensitivity the antennae must be capable of receiving the widest range of frequencies. As described in [4], we focus our attention at the 0.5-1.5THz band gaining higher resolution than typically possible in millimeter-wave range while maintaining good penetrability through most types of clothing materials.

Since the antenna is terminated by a resistive load and not by a matched transmission line, we are not constrained with 50 Ω or 75 Ω impedances for antenna output. This provides us with the freedom to choose whatever real impedance load that

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we wish and eliminate the need of sometimes cumbersome impedance matching circuits.

B. Antenna physical restrictions

Since a low-cost array of detectors is envisioned, we chose to use CMOS-SOI technology, allowing us to manufacture high precision and repeatable structures at a fairly low price and high yield. Using CMOS-SOI technology also allows us to incorporate the temperature detector coupled to the bolometer itself and the readout circuitry in the same chip.

Achieving high sensitivity means having a high temperature change of the resistive load as a result of the detected THz radiation. This requirement forces the antenna to have the lowest possible thermal conductivity to the bulk. The thermal time constant of the structure, which determines the highest possible refresh rate of the sensor, is equally important. Satisfying both requirements demands that the thermal capacitance (which is in turn dictated by its thermal mass) is lowered to its minimum.

For the reasons described above we chose the IBM CMOS 7RF SOI technology [5]. The antenna has been manufactured at the lowest metal layer, and with the thinnest line width possible. The antenna fabrication was followed by MEMS post-processing in which the surrounding oxide and the underlying silicon bulk were removed. This step is necessary to ensure low thermal capacitance and thermal conductivity to the bulk [6].

Fig. 1. Surface current distribution of a loop antenna (diamond shape) at its resonance frequency, at different phases, taken from HFSS [7]. The port is located at the blue ellipse area and the null current points always remain at the left and right corners, as expected from a standing wave.

III. ANTENNA THEORY

The antenna is based on the well known loop antenna [8], which is basically a narrow band standing wave antenna, with its center frequency located at the frequency at which the antenna perimeter length is about one wavelength, as depicted in Fig. 1. The narrow bandwidth is especially prominent in our

case, where it is important to maintain low thermal mass and thin antenna wires.

In order to transform the narrow bandwidth loop antenna into a wide bandwidth antenna, we transformed its nature from a standing wave antenna into a traveling wave antenna, allowing the current to flow in an infinite loop which does not include the port, as in Fig. 2. The port, located in the middle of the structure, is used to excite a current in the antenna. The current can flow in several different paths, depending on the frequency.

Fig. 2. Example of skirt antenna including illustration of the different current paths. Orange: antenna metal wires, Light blue: port location, Grey: illustration of the single-loop paths, Purple: illustration of a 2-loop path.

Even when the single loop path length is one wavelength, the antenna does not behave as two connected loop antennas with the same port. At all frequencies, the current path is a combination of the two single-loop paths and the 2-Loops path, as is exemplified in Fig 3.

Fig. 3. Surface current distribution of a skirt antenna when a single-loop length is one wavelength, at different phases. Null current points are represented by light green and blue arrows. The movement of the null current points is a clear indication for a traveling wave.

Owing to the 2-Loops path, the skirt antenna has much wider bandwidth compared to the loop antenna. For example, at loop length of one and a half wavelength, a loop antenna

has infinite input impedance [8], thus restricting its bandwidth. But, in the case of the skirt antenna, when the single-loop length is one and a half wavelengths, the 2-Loops path length is actually 3 wavelengths and traveling wave, excited by the port, can exist.

IV. ANTENNA DESIGN

HFSS [7] software has been employed in aid of the antenna design. Since the antenna is coupled to a bolometer (transforming electromagnetic radiation into heat), we do not characterize it using the traditional antenna metrics. For example – the ohmic loss on the antenna arms which is normally a destructive effect, might actually contribute to the antenna sensitivity by heating it up. Due to relatively low refresh-rate, the entire antenna (resistive load and antenna arms) arrives at thermal equilibrium.

The most interesting design characteristics of our antenna are the directivity (to best match the focal plane array lens [4]) and the reflection coefficient between the port and the antenna arms.

In order to ease the antenna fabrication in the silicon chip, we restricted the design only to vertical lines, horizontal lines and 45° diagonal lines. Thus, the antenna resembles half of an octagon, as in Fig. 4. Moreover, each antenna in the array is surrounded by readout lines that deliver current to the temperature detector (but the connection is not shown here).

Fig. 4. Example of (orange) skirt antenna including (green) readout lines. Pixel size is 250 x 250 μm .

The readout lines, that surround each antenna, form a loop antenna by themselves, which in turn “draws” all the electromagnetic energy at its resonance frequency, which is around 0.6-0.65THz for pixel pitch of 250 μm . For this reason, we centered the antenna bandwidth on higher frequencies.

The simulated return loss of a skirt antenna having a resistive load of 200 Ω is depicted in Fig. 5, and the antenna directivity is depicted in Fig. 6.

Fig. 5. Skirt antenna S11 simulation for the structure of Fig. 4

Fig. 6. E-plane directivity of the skirt antenna in Fig. 4

V. FINAL ANTENNA STRUCTURE

In order to get the maximal sensitivity as a bolometer, the antenna must be able to absorb THz radiation at both polarizations and with the minimal thermal mass. For this reason, we have incorporated several novelties in the skirt antenna design that prevent it from being a good transmitter, but contribute to its performance as a bolometer. The innovations include:

1. Completing the antenna arms to encircle the resistive load from all sides.
2. Adding an orthogonal resistive load to the one that was depicted before. All together the skirt antenna now has 4 resistive loads at its center.

This 2-polarization structure is depicted in Fig 7. Looking at Fig. 7, it is evident that this structure cannot function as a transmitting antenna, since if we replace the resistive loads with transmission lines with identical impedance, the energy going out of the one source would be absorbed by adjacent probe and would not be transmitted. But, this structure exhibit excellent performance as a bolometer that can absorb incoming radiation from both polarizations.

Fig. 7. Example of full octagonal skirt antenna with 4 resistive loads.

For the reasons above, it was not possible to simulate the full skirt antenna for its return loss and directivity, so we used a method that calculates the total absorption of the structure at different frequencies [9]. Using the total absorption method we found the optimal resistive load of the 2-polarization antenna to be 900Ω .

An array of the full skirt antennae has been manufactured. Fig. 8 shows a SEM picture of 6 antennae that have already been released by the post-production MEMS process. Each antenna is connected to the readout lines by a single holding arm.

Fig. 8. SEM picture of an array of 6 full skirt antennas.

The measurement of the skirt antenna has been performed at 655GHz. The measured radiation pattern was compared to the E-plane directivity simulation of the single skirt antenna from Fig. 4, since it is impossible to simulate the directivity of the full skirt antenna. A very good agreement between the measured results and the simulation is evident from Fig. 9.

VI. SUMMARY

A design of a novel wideband and low-weight skirt antenna has been presented, including extensive explanations on the physical properties of this structure. The different

design considerations are reviewed and the full design is outlined. The antenna was fabricated with a CMOS-SOI process and measured at 655GHz, showing very good agreement between the simulation and the experimental characterization.

Fig. 9. Measurement and simulation of the skirt antenna E-plane directivity at 655GHz.

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